

The Simulation of Coherent Structures in a Laminar Boundary Layer

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Introduction

Coherent structures in turbulent shear flows have been studied extensively by several techniques, including the VITA technique (Alfredsson & Johansson 1984, Blackwelder & Kaplan 1976, Johansson, Alfredsson & Eckelmann 1987) which selects rapidly accelerating or decelerating regions in the flow. "Positive" events (in which the streamwise velocity increases while passing a fixed probe) have been found (Alfredsson & Johansson 1984, Johansson, Alfredsson & Eckelmann 1987) to be inclined shear layers with a strong associated Reynolds stress. If these structures are responsible for a large part of turbulence production, then an important question is how are they formed and how do they evolve in the flow.

Present study

The motivation for the present work is the idea that the evolution of coherent structures in a turbulent flow follows simple dynamics which are not dominated by the turbulent flow field. This idea has been studied by Russell and Landahl (1984, also Landahl 1984) who developed some approximate models for the dynamics of such structures, but in order to study them more completely a full-scale calculation is necessary. Based on the assumption that the dynamics of the shear layer's evolution are largely independent of the random part of the flow, one should be able to capture the essential features by looking at the evolution of a disturbance in a laminar boundary layer. This approach has recently been illustrated in Acarlar & Smith's study of hairpin vortices (1987).

A localized disturbance was studied numerically using a three-dimensional, unsteady Navier-Stokes code (Spalart 1986). The mean flow considered was a Blasius boundary layer and the initial velocity perturbation, shown at one y-location in figure 1, was the same as that used by Russell & Landahl (1984), consisting of two pairs of counter-rotating vortices. Landahl (1984) has shown that such a flow would result from an instantaneous peak of $u'v'$, and so one would expect to find perturbations of this kind following high Reynolds-stress production in a turbulent

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flow. Analytically, the disturbance has the following form:

$$\begin{aligned} u' &= 0 \\ v' &= \frac{Axy^3(1-2z^2)}{l_z} e^{-(x^2+y^2+z^2)} \\ w' &= \frac{-Axz(3y^2-2y^4)}{l_y} e^{-(x^2+y^2+z^2)} \end{aligned}$$

where A is the amplitude of the disturbance and the coordinates are scaled by some characteristic lengths l_x , l_y , and l_z . For the cases presented, the scaling used was $l_x = 5$, $l_y = 1.2$, $l_z = 6$, and A was chosen to be 0.2. This gave an initial perturbation in v and w of about 2% and a streamwise and spanwise extent of about 10 (all velocities are normalized by the free stream, and all lengths by the displacement thickness at the point of generation). The starting Reynolds number, Re_{δ^*} , was chosen to be 945. Some calculations were also performed with a negative amplitude, $A = -0.2$, representing an initial condition of downward flow, followed by upward motion, and simulating a "negative" VITA event. Several grid resolutions and box sizes were used to ensure that there was no grid dependence. Most of the results reported here were calculated on a 64^2 grid in the horizontal planes with 40 Jacobi modes in the vertical direction. The solution at all times remains symmetric with respect to the $z = 0$ plane.

Results and discussion

Figures 2 and 3 show the evolution of the streamwise velocity perturbation u' (all of the results presented here are plotted in a frame of reference moving at $0.4U_\infty$, chosen so as to 'freeze' the structure in the plotting window). At $T = 0.0$ there is no longitudinal component of the disturbance but one quickly develops as the liftup of slower fluid creates a velocity defect region, followed by a accelerated region of fluid pulled down from the upper part of the boundary layer. Because of the mean shear, the fluid elements further from the wall will be advected faster than those closer to the wall resulting in the stretching out and intensification of the structure in the streamwise direction as it propagates downstream. This is clearly seen in the second frame, $T = 81.4$, where a strong internal shear layer has formed. The shear layer is not quite symmetric as the ejection side (downstream, where v' is positive) is somewhat stronger than the sweep side (upstream, where fluid moves toward the wall) which is in agreement with the results of Johansson, Alfredsson and Eckelmann (1987) in a turbulent flow. At a later time $T = 116.9$, the breakdown of the shear layer is becoming evident from the greatly increased amplitude and the appearance of finer scales in the disturbance velocities, although the exact nature of the breakdown is as yet unclear.

The spanwise structure of the disturbance close to the wall is seen in figure 3. What is especially striking here is the development of long "streaks" of alternating high and low speed fluid. The streak spacing is closely related to the spanwise dimension of the original disturbance.

The Reynolds stress distribution is shown in figure 4. As one would expect, $-u'v'$ increases as the disturbance grows and it is primarily concentrated in the two regions ahead and behind the shear layer. The downstream peak is stronger, consistent with the larger perturbation levels in that region. The Reynolds-stress distribution is also remarkably consistent with the structure seen in the fully turbulent flow (Johansson & Alfredsson 1982).

Figure 5 shows the amplitude of the disturbance as it propagates downstream. Two results are plotted: the solid line is the shear-layer disturbance ($A = 0.2$), while the dashed line indicates the growth of the "inverse disturbance" ($A = -0.2$). While this disturbance does grow, its growth seems to be linear, in contrast to the shear layer which grows exponentially. This dramatic difference serves to show that it is the structure of the disturbance, and not only its initial amplitude that leads to the rapid growth. One possible reflection of this in experimental results is that the frequency of detection for negative VITA events is considerably lower than for positive events. While the results are not shown here, the negative case also develops a long streaky structure and at later times an unstable shear-layer structure does develop off the center-line, perhaps hinting that it too will undergo a rapid growth when that mechanism becomes dominant.

Summary

The evolution of a localized disturbance in a laminar boundary layer shows strong similarity to the evolution of coherent structures in a turbulent wall-bounded flow. Starting from a liftup-sweep motion, a strong shear layer develops which shares many of the features seen in conditionally-sampled turbulent velocity fields. The structure of the shear layer, Reynolds stress distribution and wall pressure footprint are qualitatively the same, indicating that the dynamics responsible for the structure's evolution are simple mechanisms dependent only on the presence of a high mean shear and a wall and independent of the effects of local random fluctuations and outer flow effects. As the disturbance progressed, the development of streak-like high- and low-speed regions associated with the three-dimensionality of the disturbance was also observed.

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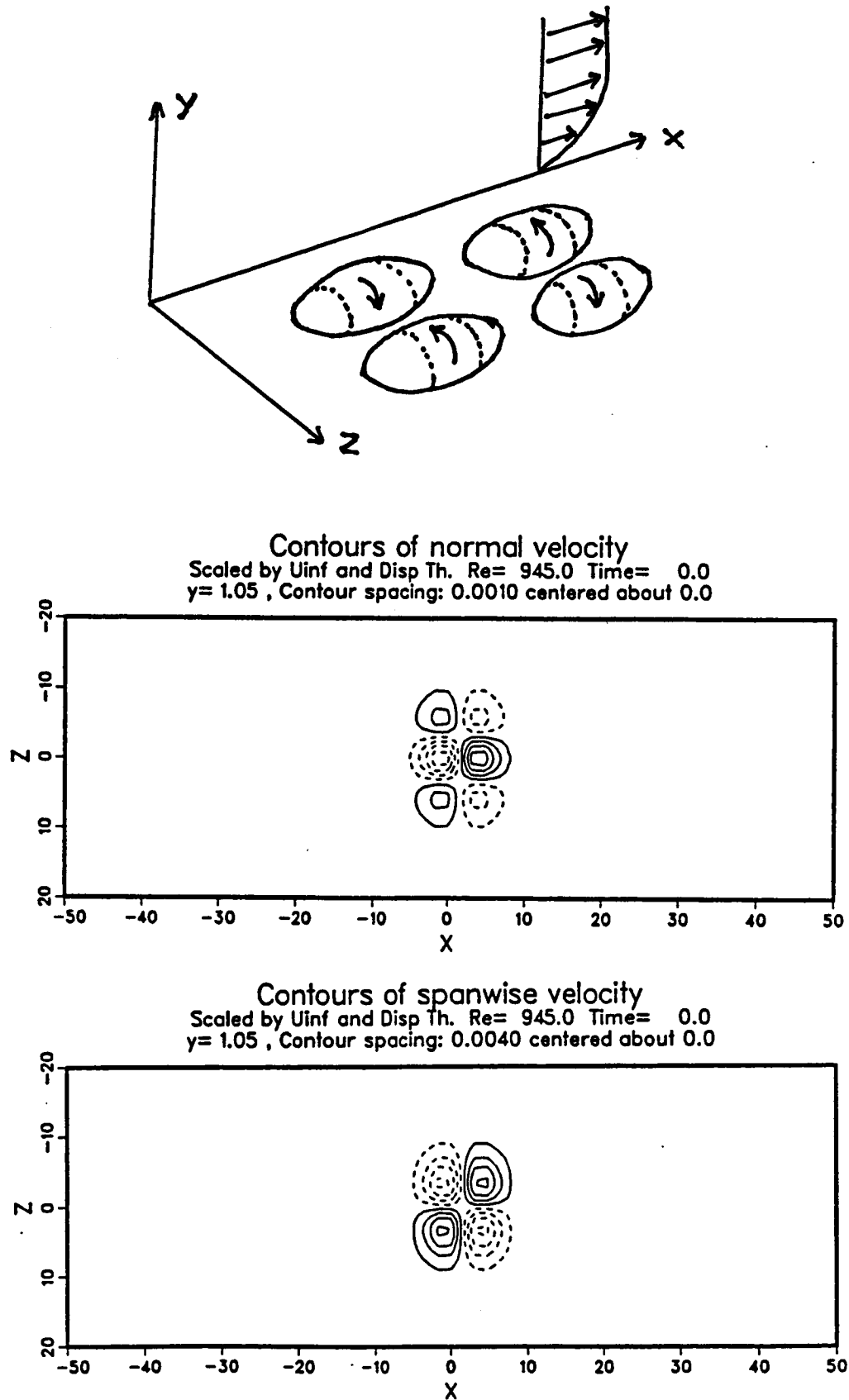


FIGURE 1. Initial disturbance. a) Sketch of vorticity field; b) and c) velocity contours.

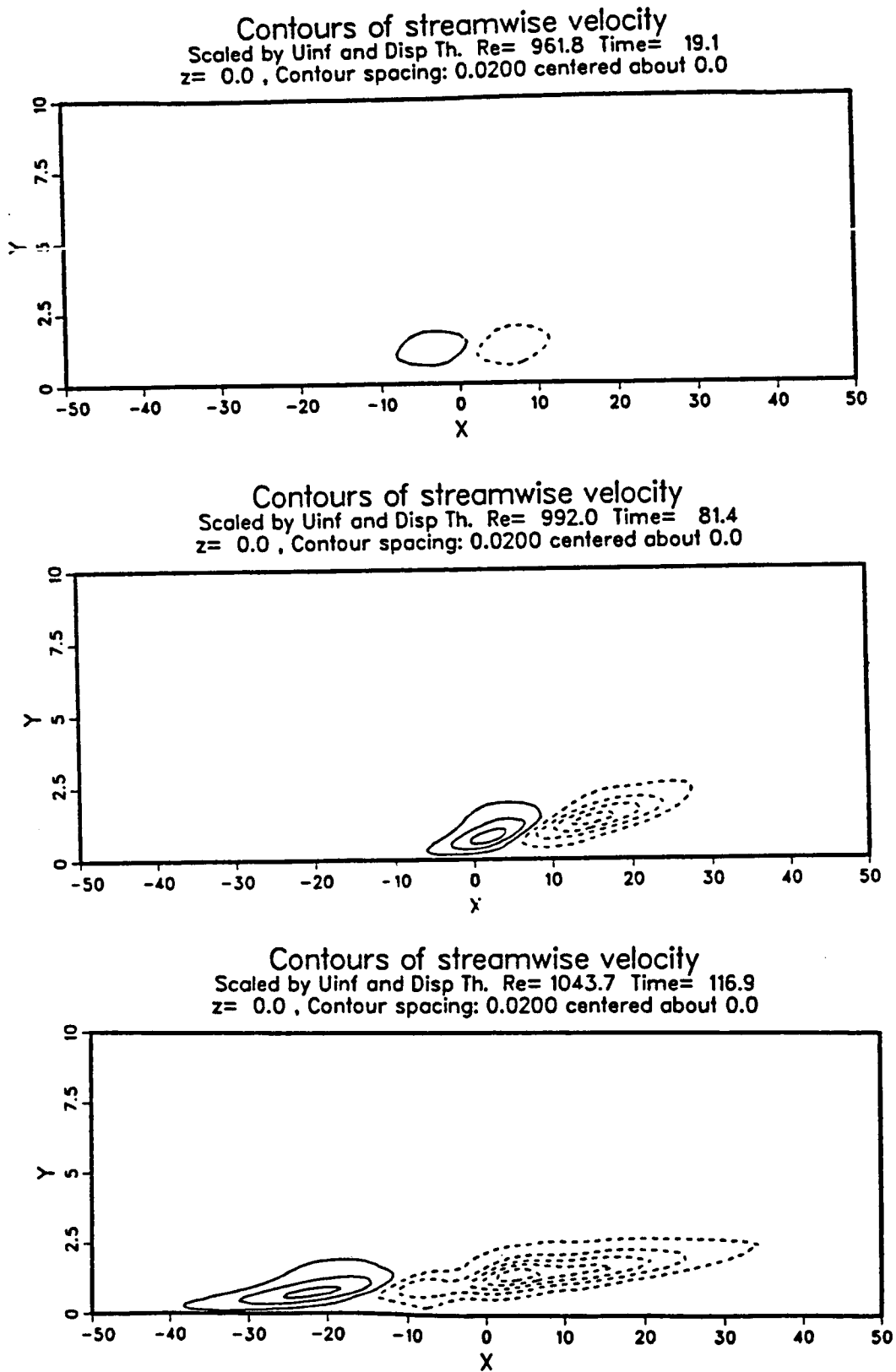


FIGURE 2. Streamwise-velocity contours at different times. Side view.

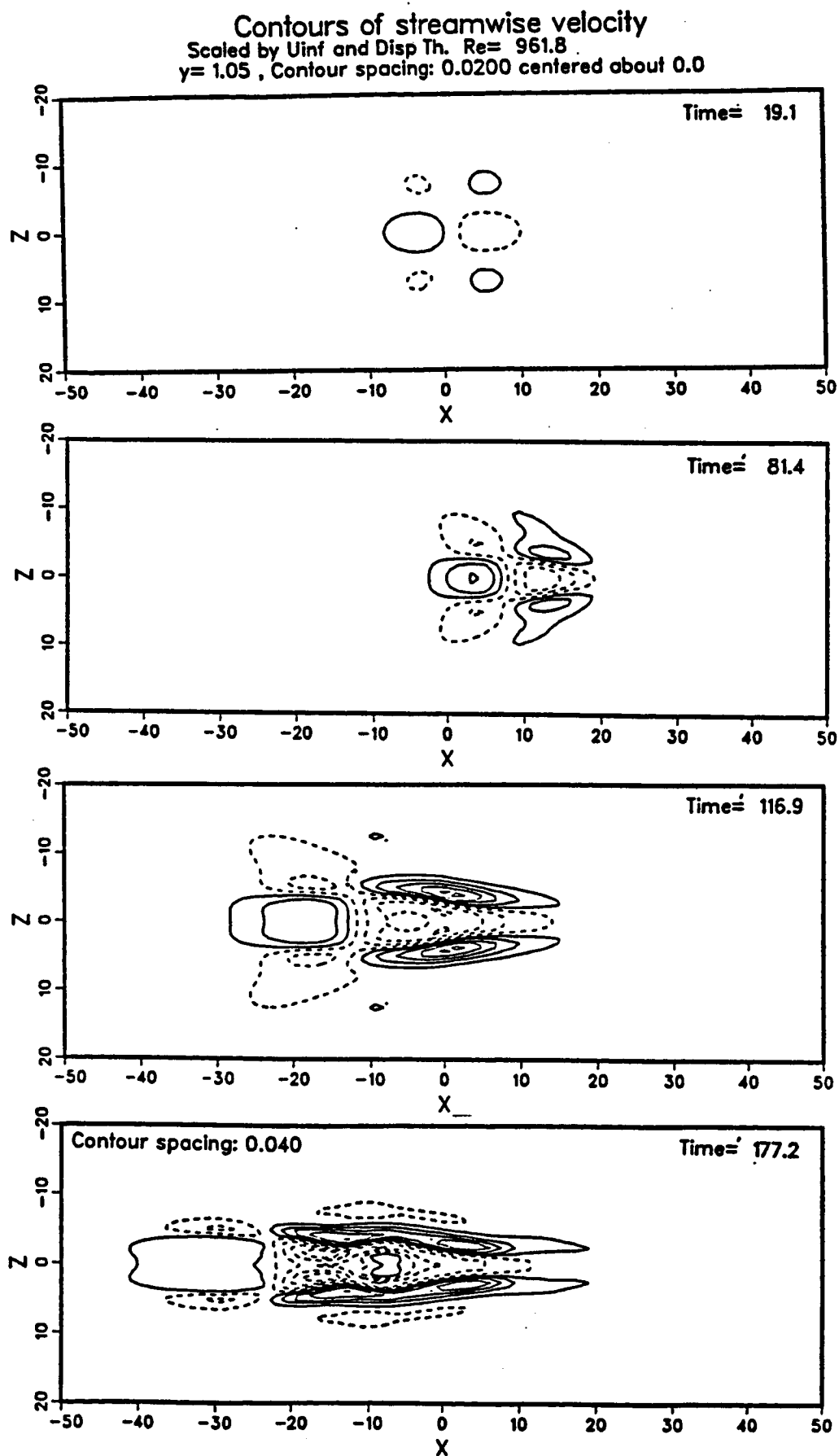


FIGURE 3. Streamwise-velocity contours at different times. Plan view.

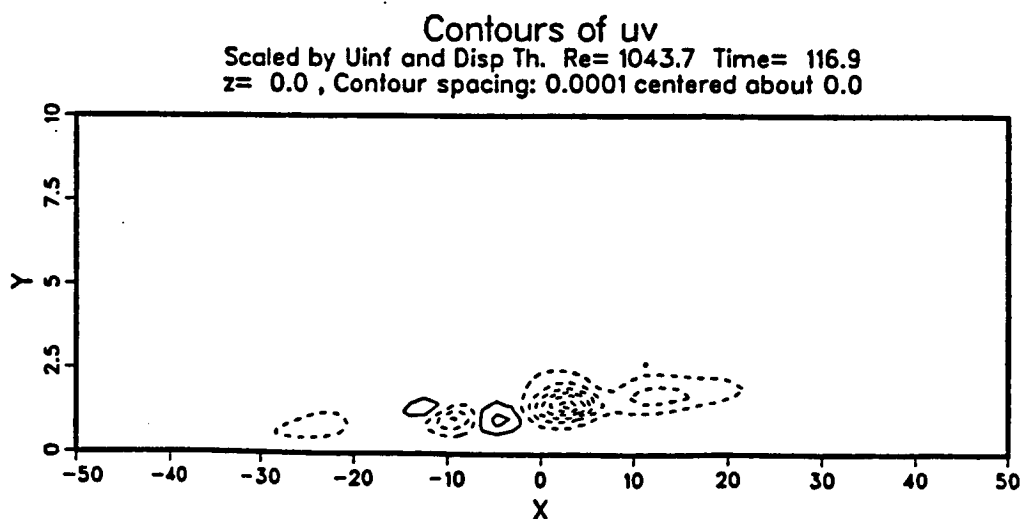
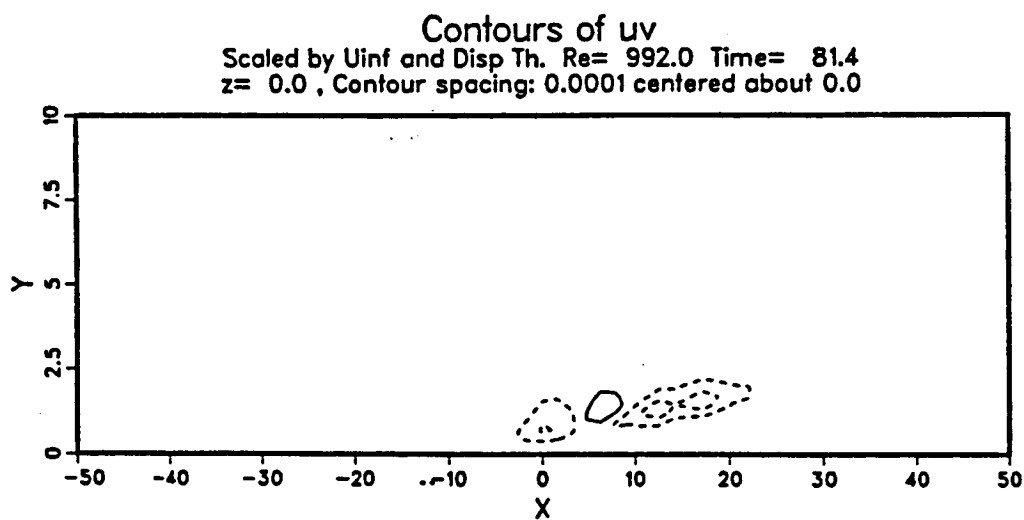
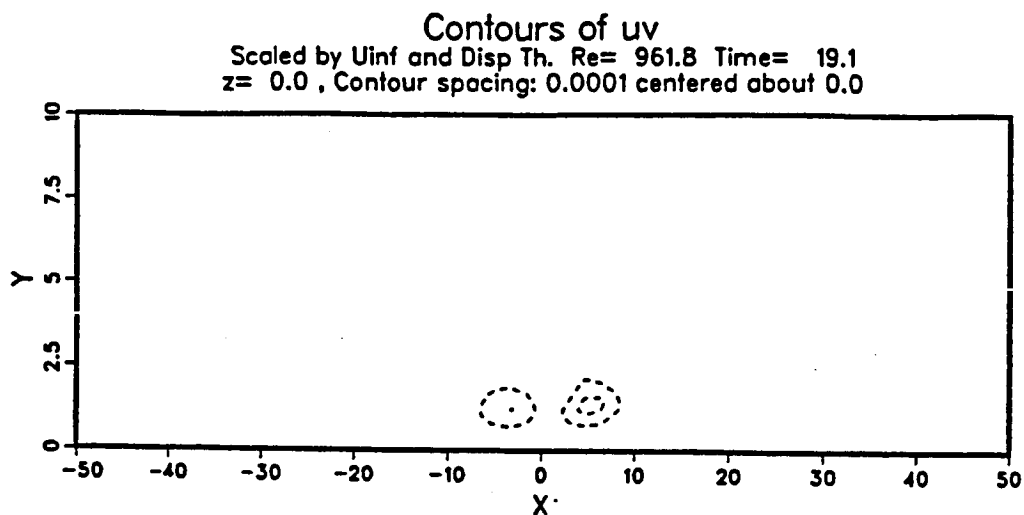


FIGURE 4. Reynolds-stress contours at different times. Side view.

Amplitude of Localized Disturbance
Normalize by U_{inf} and $Disp. Th$
Solid line: $A = 0.2$, Dotted Line: $A = -0.2$

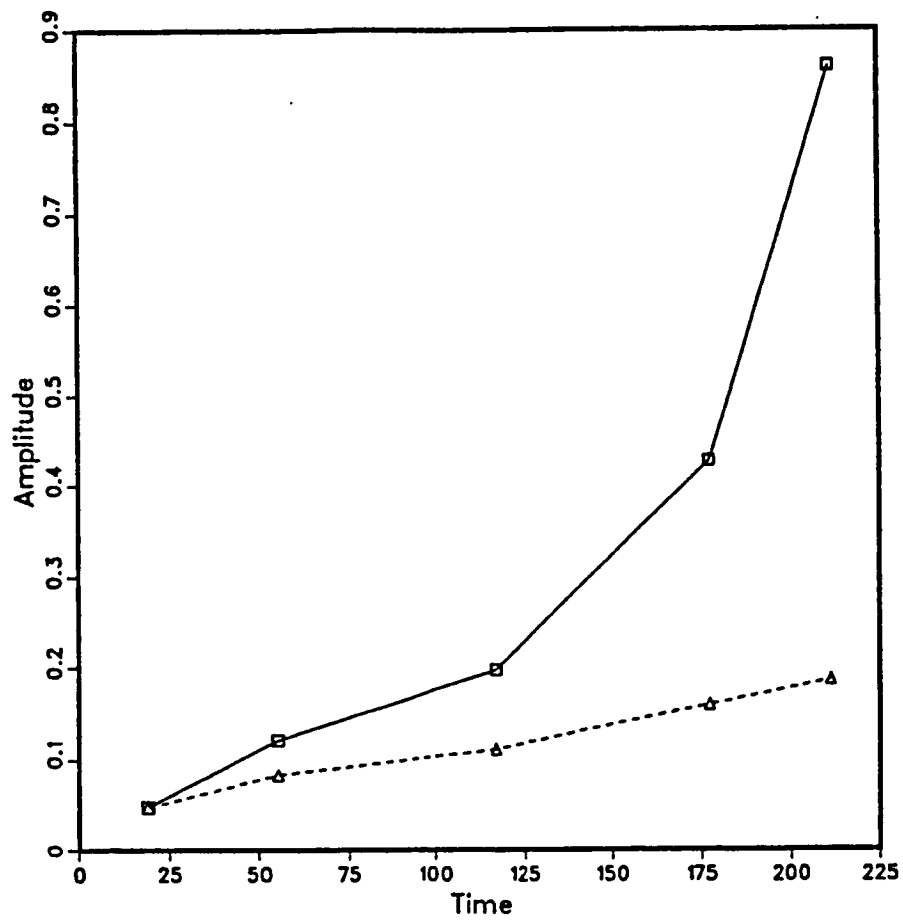


FIGURE 5. Evolution of the disturbance amplitude.